

Scaling patterns of the suppression of π^0 yields in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV: links to the transport properties of the QGP

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Suppression measurements for neutral pions (π^0) are used to investigate the predicted path length (L) and transverse momentum (p_T) dependent jet quenching patterns of the hot QCD medium produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The observed scaling patterns show the predicted trends for jet-medium interactions dominated by radiative energy loss. They also allow simple estimates of the transport coefficient \hat{q} and the ratio of viscosity to entropy density η/s . These estimates indicate that the short mean free path (λ) in the QCD medium leading to hydrodynamic-like flow with a small value of η/s , is also responsible for the strong suppression observed.

One of the important discoveries at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), has been the observation that high- p_T hadron yields are suppressed in central and mid-central A+A collisions when compared to the binary-scaled yields from p+p collisions [1]. This observation has been attributed to jet-quenching [2] – the process by which hard scattered partons interact and lose energy in the hot and dense quark gluon plasma (QGP) produced in the collisions. Subsequent to such interactions, the partons which do emerge, then fragment into topologically aligned hadrons (jets) which provide the basis for the π^0 suppression measurements.

There is considerable current interest in the use of jet quenching as a quantitative tomographic probe of the QGP. Recent theoretical efforts have centered on investigations of the energy loss mechanism for scattered partons which propagate through this medium. Two such mechanisms are; (i) scatterings off thermal partons in binary elastic collisions and (ii) Gluon bremsstrahlung with the Landau-Pomeranchuk-Migdal (LPM) [3] effect. The latter has been investigated via different formalisms [4, 5, 6, 7, 8, 9, 10]. Studies of the relative importance of both jet quenching mechanisms have also been made [11, 12, 13, 14]. To date, a conclusive mechanistic picture has not yet emerged.

Initial quantitative studies with models which incorporate the time evolution of the QGP medium via relativistic ideal (3+1)-dimensional hydrodynamical simulations, are currently underway [15, 16]. However, the value of such studies rests heavily on accurate knowledge of the dominant mechanism/s for jet quenching. Therefore, it is important to pursue validation tests which can lend insight or provide a clear distinction between different energy loss mechanisms.

The experimental probe commonly exploited for jet-quenching studies in AA collisions is the nuclear modification factor (R_{AA});

$$R_{AA}(p_T) = \frac{1/N_{\text{evt}} dN/dy dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dy dp_T},$$

where σ_{pp} is the particle production cross section in p+p

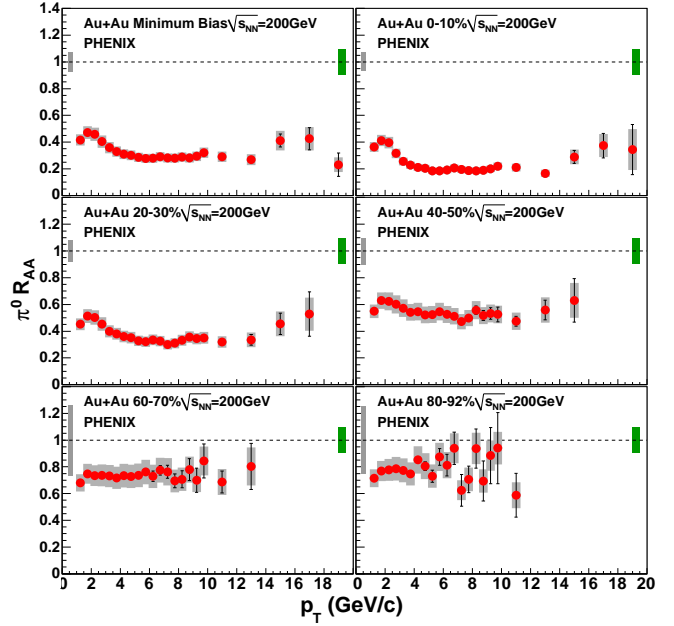


FIG. 1: (Color online) Nuclear modification factor (R_{AA}) for π^0 s reproduced from Ref. [17]. Error bars indicate statistical and p_T -uncorrelated errors; boxes indicate p_T -correlated errors. The single box around $R_{AA}=1$ on the left is the error due to N_{coll} ; the single box on the right is the overall normalization error of the p+p reference spectrum.

collisions and $\langle T_{AA} \rangle$ is the nuclear thickness function averaged over the impact parameter range associated with a given centrality selection

$$\langle T_{AA} \rangle \equiv \frac{\int T_{AA}(\mathbf{b}) d\mathbf{b}}{\int (1 - e^{-\sigma_{pp}^{\text{inel}} T_{AA}(\mathbf{b})}) d\mathbf{b}}.$$

The corresponding average number of nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle = \sigma_{pp}^{\text{inel}} \langle T_{AA} \rangle$, is routinely obtained via a Monte-Carlo Glauber-based model calculation [18, 19].

In this letter we use R_{AA} measurements to perform validation tests which addresses the question of whether or not medium induced gluon radiation is a dominant mechanism for jet-energy loss.

The measurements employed for these tests are the recently published $R_{AA}(p_T)$ and $R_{AA}(\Delta\phi, p_T)$ data for π^0 [17, 20]. Here, $\Delta\phi$ is the azimuthal angle relative to the reaction plane. A subset of these data is shown as a function of p_T for several centrality selections in Fig. 1. The minimum bias results in the top left panel indicate that, for $2.5 \lesssim p_T \lesssim 5$ GeV/c, suppression increases with p_T to the value $R_{AA} \sim 0.3$. By contrast, a much weaker p_T dependence is observed for $p_T \gtrsim 5$ GeV/c, with a hint that the suppression decreases as p_T increases. The same trends are evident for all centrality selections spanning central and mid-central collisions, albeit with different absolute magnitudes. These trends provide an important constraint for our tests, as discussed below.

To perform validation tests on the data for medium induced gluon radiation, we use the “pocket formula” of Dokshitzer and Kharzeev (DK) [8]. This formula gives the quenching of the transverse momentum spectrum for jets produced from scattered light partons [8] as;

$$R_{AA}(p_T, L) \simeq \exp \left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q} \frac{\mathcal{L}}{p_T}} \right] \quad (1)$$

$$\mathcal{L} \equiv \frac{d}{d \ln p_T} \ln \left[\frac{d\sigma_{pp}}{dp_T^2}(p_T) \right],$$

where α_s is the strong interaction coupling strength, C_F is the color factor, L is the path length [of the medium] that the parton traverses and \hat{q} is the transport coefficient which reflects the squared average transverse momentum exchange per unit path length, between the medium and the parton.

Here, there are two essential points. First, Eq. 1 is derived with an explicit assumption that the mechanism for energy loss is medium induced gluon radiation [21]. Second, this equation gives specific testable predictions for the dependence of $R_{AA}(p_T, L)$ on L and p_T for $p_T > 5$ GeV/c. That is, $\ln[R_{AA}(p_T, L)]$ should scale as L and $1/\sqrt{p_T}$ respectively (ie. $\ln[R_{AA}(p_T, L)]$ should show a linear dependence on both L and $1/\sqrt{p_T}$ if medium induced gluon radiation is indeed the dominant energy loss mechanism).

To study the L dependence, the transverse size of the system \bar{R} was used as an estimate for the angle averaged path length L , as well as to determine its value in- (L_x) and out- (L_y) of the reaction plane. For each centrality selection, the number of participant nucleons N_{part} , was estimated via a Monte-Carlo Glauber-based model [18, 19]. The corresponding transverse size \bar{R} was then determined from the distribution of these nucleons in the transverse (x, y) plane via the same Monte-Carlo Glauber model:

$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2} \right)},$$

where σ_x and σ_y are the respective root-mean-square widths of the density distributions; here, averaging is performed over configurations. For these calculations, the

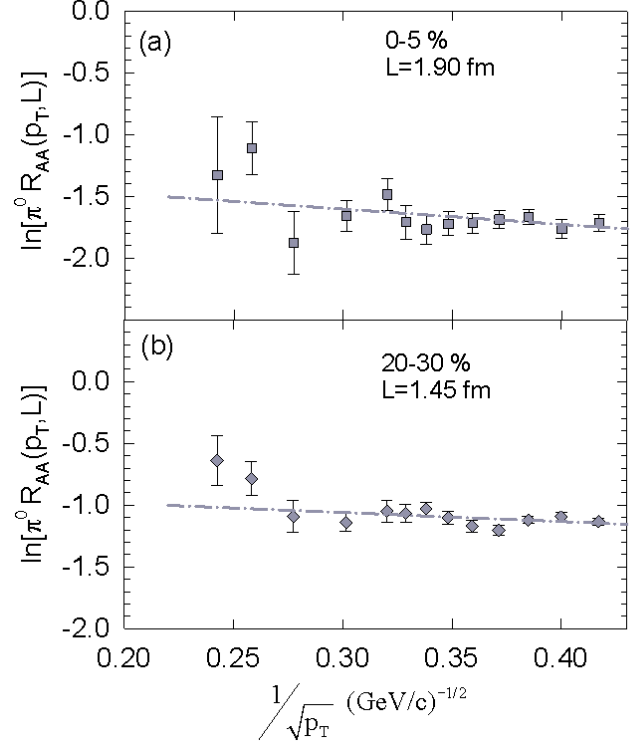


FIG. 2: (Color online) $\ln[R_{AA}(p_T, L)]$ vs. $1/\sqrt{p_T}$ ($p_T \gtrsim 5$ GeV/c) for centrality selections of 0-5% (a) and 20-30% (b). Error bars are statistical only. p_T -correlated systematic errors are about 12% and the systematic errors associated with N_{coll} and the overall normalization of the p+p reference spectrum are $\sim 7\%$ and 10% respectively. The dot-dashed curve in each panel is a fit to the data (see text).

initial entropy profile in the transverse plane was assumed to be proportional to a linear combination of the number density of participants and binary collisions [22, 23]. The latter assures that the entropy density weighting is constrained by hadron multiplicity measurements.

The results from our validation tests for medium-induced gluon radiation are summarized in Figs. 2 – 4. Figs. 2 (a) and (b) show plots of $\ln[R_{AA}(p_T, L)]$ vs. $1/\sqrt{p_T}$ for $p_T \gtrsim 5$ GeV/c and centrality selections of 0-5% ($L=1.90$ fm) and 20-30% ($L=1.45$ fm) respectively. The dot-dashed curves in these figures represent a linear fit to the data. They show that, although there is some scatter, the trend of the data is compatible with the $1/\sqrt{p_T}$ dependence predicted by Eq. 1. It is worth mentioning here that a similar $1/\sqrt{p_T}$ dependence is observed for the range $2.5 \lesssim p_T \lesssim 5$ GeV/c, but with a different (positive) slope.

Figure 3 shows the L dependence of $\ln[R_{AA}(p_T, L)]$ for two different p_T selections as indicated. The dot-dashed curve shows a linear fit to the data for $p_T > 5$ GeV/c and $L \gtrsim 0.65$ fm, ie. the two data points corresponding to the two most peripheral collision centralities were excluded

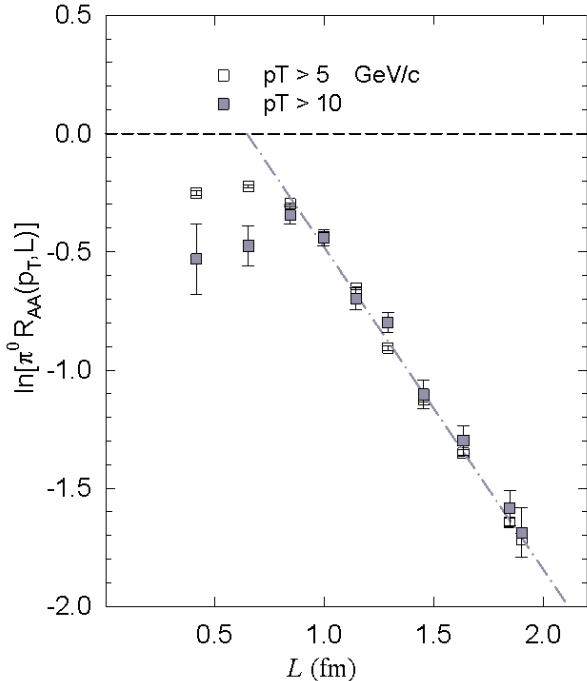


FIG. 3: (Color online) $\ln[R_{AA}(p_T, L)]$ vs. L for two p_T selections as indicated. Error bars are statistical only. The systematic error associated with N_{coll} ranges from $\sim 7\%$ in central collisions to $\sim 30\%$ in peripheral collisions; the systematic error resulting from overall normalization of the p+p reference spectrum is about 10% (cf. Fig.1). The dot-dashed curve is a linear fit to the data set for $p_T > 5$ GeV/c (see text).

from the fit (note the large N_{coll} systematic errors for peripheral collisions). Fig. 3 shows that the data trends for both p_T selections ($p_T > 5$ and $p_T > 10$ GeV/c), validates the linear dependence on L predicted by Eq. 1. The efficacy of this scaling pattern is not significantly influenced by systematic errors.

Further evidence for this linear dependence is also evident in Fig. 4 where we show results for R_{AA} measurements in- and out of the reaction plane for π^0 s with $5 < p_T < 8$ GeV/c [20]. Panel (a) shows that, for the same number of participants, π^0 suppression is larger out-of-plane than it is in-plane. However, panel (b) shows that, when plotted as $\ln[R_{AA}(p_T, L_{x,y})]$ vs. L_x and L_y , the in-plane and out-of-plane data show a single linear dependence on $L_{x,y}$. This same dependence is found for all other reaction plane orientations for $p_T \gtrsim 5$ GeV/c. This confirms that the azimuthal anisotropy of particle yields (at high p_T) stem from the path-length dependence of jet quenching. The dashed curve (fit to the data) in the figure reinforces the predicted linear dependence of these data on the path length (cf. Eq. 1).

The fits to the data in Fig. 3 (for the two p_T cuts) indicate an intercept $L \approx 0.6$ fm, which suggests a minimum path length requirement for the initiation of π^0 suppression.

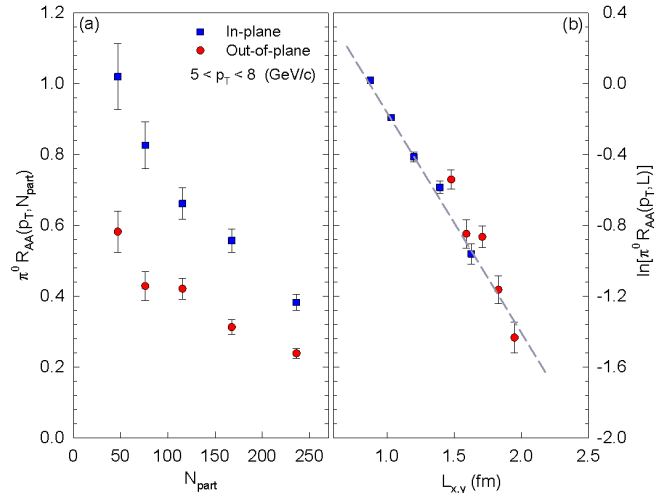


FIG. 4: (Color online) (a) $R_{AA}(p_T, N_{\text{part}})$ vs. N_{part} for π^0 's detected in- and out of the reaction plane. The data are taken from Ref. [20] for the selection $5 < p_T < 8$ GeV/c. Error bars are statistical only. (b) $\ln[R_{AA}(p_T, L)]$ vs. $L_{x,y}$, the path length in- and out of the reaction plane. The systematic errors for both (a) and (b) are similar to those of Fig. 3. The dashed curve is a linear fit to the data.

tion. Such a requirement is akin to the plasma formation or cooling times proposed in Refs. [24, 25].

The corresponding slopes (for $p_T > 5$ and $p_T > 10$ GeV/c) indicate similar magnitudes with a hint of a small decrease in slope with increasing $\langle p_T \rangle$. This relatively weak p_T dependence (which is also reflected in Fig. 2), could be an indication that \hat{q} has a dependence on p_T , eg. $\hat{q} = \hat{q}_0 \left(\frac{p_T}{p_0} \right)^\lambda$ where λ is a small fractional power [26].

To obtain an estimate of the magnitude of \hat{q} , we use Eq. 1 in conjunction with the slope, $-1.26 \pm 0.06 \text{ fm}^{-1}$, extracted from Fig. 3 for $p_T > 10$ GeV/c. This gives the value $\hat{q} \approx 0.75 \text{ GeV}^2/\text{fm}$ for the values $\alpha_s = 0.3$ [16], $C_F = 9/4$ [8, 27] and $\mathcal{L} = n = 8.1 \pm 0.05$ [20]. This estimate of \hat{q} , which can be interpreted as a space-time average, is comparable to the recent estimates of $\sim 1\text{--}2 \text{ GeV}^2/\text{fm}$ obtained from fits to hadron suppression data (for the most central Au+Au collisions) within the framework of the higher twist (HT) expansion [28, 29] and the Gyulassy-Levai-Vitev (GLV) scheme [30, 31]. It is, however, much less than the value recently extracted via the approach of Arnold, Moore and Yaffe (AMY) [16, 32] and that of Armesto Salgado and Wiedemann (ASW) [16, 33].

The ratio of the shear viscosity (η) to the entropy density (s) can also be estimated as [34];

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$

where T is the temperature. This estimate can be compared to the value of $4\pi \frac{\eta}{s} \approx 1.3 \pm 0.3$ extracted from flow data [23] for $T \sim 220 \text{ MeV}$ [35]. It is noteworthy

that if we use this same temperature in conjunction with our extracted value for \hat{q} (in the above equation), we obtain a strikingly similar estimate for η/s . We conclude therefore, that the relatively short mean free path in the plasma [23] which drives hydrodynamic-like flow with small shear viscosity, is also responsible for the strong jet quenching observed.

In summary, we have performed validation tests of the scaling properties of jet quenching to investigate the dominant mechanism for jet-energy loss. Our tests confirm the weak $1/\sqrt{p_T}$ dependence, as well as the linear dependence on path length (L and $L_{x,y}$) predicted by Dokshitzer and Kharzeev, for jet suppression dominated by the mechanism of medium-induced gluon radiation in a hot and dense QGP. The quenching patterns indicate a minimum path length requirement for the initiation of π^0 suppression (corona), suggests a possible p_T dependence for \hat{q} and gives the estimate $\hat{q} \sim 1 \text{ GeV}^2/\text{fm}$ which is comparable to that obtained within the framework of

the HT and GLV models. This estimate also indicates a small value of η/s which is in good agreement with that obtained via flow measurements. The present study will have to be extended to the heavy quark systems to arrive at an even more definitive conclusion about the role of a perturbative radiative energy loss mechanism. Nonetheless, these results will undoubtedly provide important model constraints in future attempts to use jet-quenching as a quantitative tomographic probe of the QGP.

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- [1] K. Adcox et al. (PHENIX), Phys. Rev. Lett. **88**, 022301 (2002), nucl-ex/0109003.
 - [2] M. Gyulassy and X.-n. Wang, Nucl. Phys. **B420**, 583 (1994), nucl-th/9306003.
 - [3] A. B. Migdal, Phys. Rev. **103**, 1811 (1956).
 - [4] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff, Nucl. Phys. **B483**, 291 (1997), hep-ph/9607355.
 - [5] A. Kovner and U. A. Wiedemann (2003), hep-ph/0304151.
 - [6] B. G. Zakharov, JETP Lett. **63**, 952 (1996), hep-ph/9607440.
 - [7] M. Gyulassy, P. Levai, and I. Vitev, Nucl. Phys. **B594**, 371 (2001), nucl-th/0006010.
 - [8] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. **B519**, 199 (2001), hep-ph/0106202.
 - [9] X.-N. Wang and X.-f. Guo, Nucl. Phys. **A696**, 788 (2001), hep-ph/0102230.
 - [10] A. Majumder and B. Muller, Phys. Rev. **C77**, 054903 (2008), 0705.1147.
 - [11] M. G. Mustafa and M. H. Thoma, Acta Phys. Hung. **A22**, 93 (2005), hep-ph/0311168.
 - [12] A. Adil, M. Gyulassy, W. A. Horowitz, and S. Wicks, Phys. Rev. **C75**, 044906 (2007), nucl-th/0606010.
 - [13] B. G. Zakharov, JETP Lett. **86**, 444 (2007), 0708.0816.
 - [14] T. Renk, Phys. Rev. **C76**, 064905 (2007), 0708.4319.
 - [15] G.-Y. Qin et al., Phys. Rev. Lett. **100**, 072301 (2008), 0710.0605.
 - [16] S. A. Bass et al., Phys. Rev. **C79**, 024901 (2009), 0808.0908.
 - [17] A. Adare et al. (PHENIX), Phys. Rev. Lett. **101**, 232301 (2008), 0801.4020.
 - [18] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Ann. Rev. Nucl. Part. Sci. **57**, 205 (2007), nucl-ex/0701025.
 - [19] B. Alver et al., Phys. Rev. Lett. **98**, 242302 (2007).
 - [20] S. S. Adler et al. (PHENIX), Phys. Rev. **C76**, 034904 (2007), nucl-ex/0611007.
 - [21] Radiative energy loss is expected to grow quadratically with path length while elastic energy loss is expected to grow linearly (see for example Ref. [14]).
 - [22] T. Hirano and Y. Nara (2009), 0904.4080.
 - [23] R. A. Lacey, A. Taranenko, and R. Wei (2009), 0905.4368.
 - [24] V. S. Pantuev, JETP Lett. **85**, 104 (2007), hep-ph/0506095.
 - [25] J. Liao and E. V. Shuryak, Nucl. Phys. **A775**, 224 (2006), hep-ph/0508035.
 - [26] J. Casalderrey-Solana and X.-N. Wang, Phys. Rev. **C77**, 024902 (2008), 0705.1352.
 - [27] Here, it is assumed that π^0 s are dominantly produced via the fragmentation of gluons.
 - [28] H. Zhang, J. F. Owens, E. Wang, and X.-N. Wang, Phys. Rev. Lett. **98**, 212301 (2007), nucl-th/0701045.
 - [29] A. Majumder, C. Nonaka, and S. A. Bass, Phys. Rev. **C76**, 041902 (2007), nucl-th/0703019.
 - [30] M. Gyulassy, P. Levai, and I. Vitev, Phys. Rev. Lett. **85**, 5535 (2000), nucl-th/0005032.
 - [31] A. Majumder, J. Phys. **G34**, S377 (2007), nucl-th/0702066.
 - [32] G.-Y. Qin et al., Phys. Rev. **C76**, 064907 (2007), 0705.2575.
 - [33] U. A. Wiedemann, Nucl. Phys. **B582**, 409 (2000), hep-ph/0003021.
 - [34] A. Majumder, B. Muller, and X.-N. Wang, Phys. Rev. Lett. **99**, 192301 (2007), hep-ph/0703082.
 - [35] A. Adare et al. (PHENIX) (2008), 0804.4168.